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Reconnection in turbulent astrophysical fluids

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Abstract. Magnetic reconnection is a fundamental process of magnetic field topology change. We analyze the connection of this process with turbulence which is ubiquitous in astrophysical environments. We show how Lazarian & Vishniac (1999) model of turbulent reconnection is connected to the experimentally proven concept of Richardson diffusion and discuss how turbulence violates the generally accepted notion of magnetic flux freezing. We note that in environments that are laminar initially turbulence can develop as a result of magnetic reconnection and this can result in flares of magnetic reconnection in magnetically dominated media. In particular, magnetic reconnection can initially develop through tearing, but the transition to the turbulent state is expected for astrophysical systems.

1. Introduction

Magnetic fields modify fluid dynamics and it is generally believed that magnetic fields embedded in a highly conductive fluid retain their topology for all time due to the magnetic fields being frozen-in (Alfvén 1943; Parker 1979). Nevertheless, highly conducting ionized astrophysical objects, like stars and galactic disks, show evidence of changes in topology, i.e. “magnetic reconnection”, on dynamical time scales (Parker 1970; Lovelace 1976; Priest & Forbes 2002).

In this short review we argue that the concept of magnetic flux being frozen must be seriously modified to account for turbulence, which induces fast magnetic reconnection. The focus of the discussion in this review is (Lazarian & Vishniac 1999, henceforth LV99) model of reconnection in turbulent fluids¹ and its consequences. A more detailed discussion of this phenomenon can be found in our extensive review, i.e. in

¹We discuss weakly turbulent fluids which is a natural generalization of a traditional Sweet-Parker treatment of laminar fluxes. Thus LV99 should not be understood as the scheme of reconnection of magnetic field which is violently bend at all scales up to the dissipation one.

Lazarian et al. (2014). We may add that some aspects of turbulent reconnection are illuminated in other recent reviews i.e. Browning & Lazarian (2013) and Karimabadi & Lazarian (2013). The first one analyzes the reconnection in relation to solar flares, the other provides the comparison of the PIC simulations of the reconnection in collisionless plasmas with the reconnection in turbulent MHD regime. At the same time we would like to stress that while in Karimabadi & Lazarian (2013) the solar wind data analysis is presented as supporting the importance of plasma effects in reconnection, our present work in progress shows, on the contrary, good correspondence of the solar wind reconnection with the predictions of LV99 model.

2. Turbulent reconnection: history of ideas

The first attempts to appeal to turbulence in order to enhance the reconnection rate were made more than 40 years ago. For instance, some papers have concentrated on the effects that turbulence induces on the microphysical level (Speiser 1970; Jacobson & Moses 1984). However, these effects are insufficient to produce reconnection speeds comparable to the Alfvén speed in most astrophysical environments.

“Hyper-resistivity” (Strauss 1986; Bhattacharjee & Hameiri 1986; Hameiri & Bhattacharjee 1987; Diamond & Malkov 2003) is a more subtle attempt to derive fast reconnection from turbulence within the context of mean-field resistive MHD. The form of the parallel electric field can be derived from magnetic helicity conservation. Nevertheless, integrating by parts one obtains a term which looks like an effective resistivity proportional to the magnetic helicity current. In addition, there are several assumptions implicit in this derivation. The most important objection to this approach is that by adopting a mean-field approximation, one is already assuming some sort of small-scale smearing effect, equivalent to fast reconnection. Furthermore, the integration by parts involves assuming a large scale magnetic helicity flux through the boundaries of the exact form required to drive fast reconnection. The problems of the hyper-resistivity approach are discussed in detail in LV99 as well as in Eyink et al. (2011). We believe that this this approach is not fruitful.

A more productive development was related to studies of instabilities of the reconnection layer. Strauss (1988) examined the enhancement of reconnection through the effect of tearing mode instabilities within current sheets. However, the resulting reconnection speed enhancement is roughly what one would expect based simply on the broadening of the current sheets due to internal mixing. We note, however, that in a more recent work Shibata & Tanuma (2001) extended the concept suggesting that tearing may result in fractal reconnection taking place on very small scales. Waelbroeck (1989) considered not the tearing mode, but the resistive kink mode to accelerate reconnection. The numerical studies of tearing have become an important avenue for more recent reconnection research (Loureiro et al. 2009; Bhattacharjee et al. 2009). As we discuss later in realistic 3D settings tearing instability develops turbulence (Karimabadi & Lazarian 2013; Beresnyak 2013)) which induces a transfer from laminar to turbulent reconnection².

²Also earlier works suggest such a transfer (Dahlburg et al. 1992; Dahlburg & Karpen 1994; Dahlburg 1997; Ferraro & Rogers 2004)

Finally, a study of 2D magnetic reconnection in the presence of external turbulence was done by Matthaeus & Lamkin (1985, 1986). An enhancement of the reconnection rate was reported, but the numerical setup precluded the calculation of a long term average reconnection rate. One may argue that bringing in the Sweet-Parker model of reconnection magnetic field lines closer to each other one can enhance the instantaneous reconnection rate, but this does not mean that averaged long term reconnection rate increases. This, combined with the absence of the theoretical predictions of the expected reconnection rates makes it difficult to make definitive conclusions from the study. Note that, as we discussed in Eyink et al. (2011), the nature of turbulence is different in 2D and 3D. Therefore, the effects accelerating magnetic reconnection mentioned in the aforementioned 2D studies, i.e. formation of X-points, compressions, may be relevant for 2D set ups, but not relevant for the 3D astrophysical reconnection. We stress, that these effects are not invoked in the model of the turbulent reconnection that we discuss below.

In a sense, the above study is the closest predecessor of LV99 work that we deal below. However, there are very substantial differences between the approach of LV99 and Matthaeus & Lamkin (1985). For instance, LV99, as is clear from the text below, uses an analytical approach and, unlike Matthaeus & Lamkin (1985), (a) provides analytical expressions for the reconnection rates; (b) identifies the broadening arising from magnetic field wandering as the mechanism for inducing fast reconnection; (c) deals with 3D turbulence and identifies incompressible Alfvénic motions as the driver of fast reconnection.

3. 3D reconnection in weakly turbulent fluid

As astrophysical turbulence is ubiquitous, considering astrophysical reconnection in laminar environments is not realistic. As a natural generalization of the Sweet-Parker model it is appropriate to consider 3D magnetic field wandering induced by turbulence as in LV99. The corresponding model of magnetic reconnection is illustrated by Figure 1.

Like the Sweet-Parker model, the LV99 model deals with a generic configuration, which should arise naturally as magnetic flux tubes try to make their way one through another. This avoids the problems related to the preservation of wide outflow which plagues attempts to explain magnetic reconnection via Petschek-type solutions (Petschek 1964). In this model if the outflow of reconnected flux and entrained matter is temporarily slowed down, reconnection will also slow down, but, unlike Petschek solution, will not change the nature of the solution.

The major difference between the Sweet-Parker model and the LV99 model is that while in the former the outflow is limited by microphysical Ohmic diffusivity, in the latter model the large-scale magnetic field wandering determines the thickness of outflow. Thus LV99 model does not depend on resistivity and, depending on the level of turbulence, can provide both fast and slow reconnection rates. This is a very important property for explaining observational data related to reconnection flares.

Ultimately, the magnetic field lines will dissipate due to microphysical effects, e.g. Ohmic resistivity. However, it is important to understand that in the LV99 model only a small fraction of any magnetic field line is subject to direct Ohmic annihilation. The fraction of magnetic energy that goes directly into heating the fluid approaches zero as the fluid resistivity vanishes.

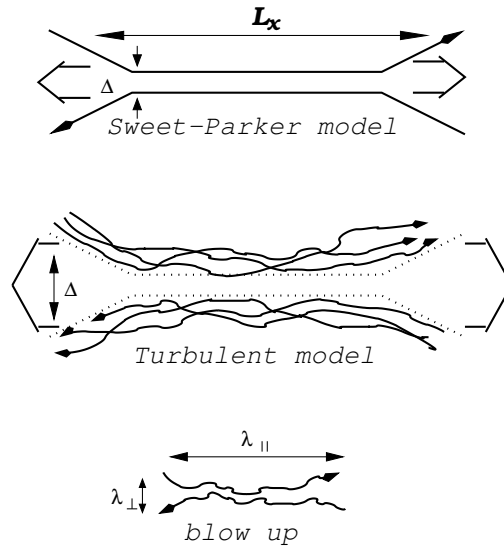


Figure 1. *Upper plot:* Sweet-Parker model of reconnection. The outflow is limited to a thin width δ , which is determined by Ohmic diffusivity. The other scale is an astrophysical scale $L \gg \delta$. Magnetic field lines are assumed to be laminar. *Middle plot:* Turbulent reconnection model that accounts for the stochasticity of magnetic field lines. The stochasticity introduced by turbulence is weak and the direction of the mean field is clearly defined. The outflow is limited by the diffusion of magnetic field lines, which depends on macroscopic field line wandering rather than on microscales determined by resistivity. *Low plot:* An individual small scale reconnection region. The reconnection over small patches of magnetic field determines the local reconnection rate. The global reconnection rate is substantially larger as many independent patches reconnect simultaneously. Conservatively, the LV99 model assumes that the small scale events happen at a slow Sweet-Parker rate. Following Lazarian et al. (2004).

The rates obtained in LV99 study are:

$$V_{rec} \approx V_A \min \left[\left(\frac{L_x}{L_i} \right)^{1/2}, \left(\frac{L_i}{L_x} \right)^{1/2} \right] \mathcal{M}_A^2, \quad (1)$$

where $V_A \mathcal{M}_A^2$ is proportional to the turbulent eddy speed. This limit on the reconnection speed is fast, both in the sense that it does not depend on the resistivity, and in the sense that it represents a large fraction of the Alfvén speed when L_i and L_x are not too different and \mathcal{M}_A is not too small. At the same time, Eq. (1) can lead to rather slow reconnection velocities for extreme geometries or small turbulent velocities.

4. LV99 model and Richardson diffusion

Magnetic reconnection in LV99 model was described using magnetic field wandering which, in general, also represents the snapshot of the Richardson diffusion of magnetic field in space (see Eyink et al. 2011). The phenomenon of Richardson diffusion is easy to understand. At the scales less than the scale of injection of the strong MHD turbulence, i.e. for $l < l_{trans}$ (LV99, Lazarian 2006),

$$l_{trans} \sim L(V_L/V_A)^2 \equiv L\mathcal{M}_A^2. \quad (2)$$

the magnetic field lines exhibit accelerated diffusion. Indeed, the separation between two particles $dl(t)/dt \sim v(l)$ for Kolmogorov turbulence is $\sim \alpha_t l^{1/3}$, where α is proportional to a cube-root of the energy cascading rate, i.e. $\alpha_t \approx V_L^3/L$ for turbulence injected with superAlvenic velocity V_L at the scale L . The solution of this equation is

$$l(t) = [l_0^{2/3} + \alpha_t(t - t_0)]^{3/2}, \quad (3)$$

which provides Richardson diffusion or $l^2 \sim t^3$. The accelerating character of the process is easy to understand physically. Indeed, the larger the separation between the particles, the faster the eddies that carry the particles apart. It is clear that Richardson diffusion is not an ordinary diffusion with square separation increasing with time, but a superdiffusion that cannot be described by a simple diffusion equation.

Eyink et al. (2011) re-derived LV99 expressions for the reconnection rate from the time dependent Richardson diffusion. This provides a way to understand the applicability of LV99 approach to more involved cases, e.g. for the case of fluid with viscosity much larger than magnetic diffusivity, i.e. the high Prandtl number fluids. A partially ionized gas is an example of such a fluids, which is essential to understand in terms of star formation.

In high Prandtl number media the GS95-type turbulent motions decay at the scale $l_{\perp,crit}$, which is much larger than the scale of at which Ohmic dissipation gets important. Thus over a range of scales less than $l_{\perp,crit}$ magnetic fields preserve their identity and are being affected by the shear on the scale $l_{\perp,crit}$. This is the regime of turbulence described in Cho et al. (2002) and Lazarian et al. (2004). In view of the findings in Eyink et al. (2011) to establish when magnetic reconnection is fast and obeys the LV99 predictions one should establish the range of scales at which magnetic fields obey Richardson diffusion. It is easy to see that the transition to the Richardson diffusion happens when field lines get separated by the perpendicular scale of the critically

damped eddies $l_{\perp,crit}$. The separation in the perpendicular direction starts with the scale r_{init} follows the Lyapunov exponential growth with the distance l measured along the magnetic field lines, i.e. $r_{init} \exp(l/l_{\parallel,crit})$, where $l_{\parallel,crit}$ corresponds to critically damped eddies with $l_{perp,crit}$. It seems natural to associate r_{init} with the separation of the field lines arising from Ohmic resistivity on the scale of the critically damped eddies

$$r_{init}^2 = \eta l_{\parallel,crit} / V_A, \quad (4)$$

where η is the Ohmic resistivity coefficient.

In this formulation the problem of magnetic line separation is similar to the anisotropic analog of the Rechester & Rosenbluth (1978) problem (see Narayan & Medvedev 2003; Lazarian 2006) and therefore distance to be covered along magnetic field lines before the lines separate by the distance larger than the perpendicular scale of viscously damped eddies is equal to

$$L_{RR} \approx l_{\parallel,crit} \ln(l_{\perp,crit} / r_{init}) \quad (5)$$

Taking into account Eq. (4) and that

$$l_{\perp,crit}^2 = \nu l_{\parallel,crit} / V_A, \quad (6)$$

where ν is the viscosity coefficient. Thus Eq. (5) can be rewritten

$$L_{RR} \approx l_{\parallel,crit} \ln Pt \quad (7)$$

where $Pt = \nu/\eta$ is the Prandtl number.

If the current sheets are much longer than L_{RR} , then magnetic field lines undergo Richardson diffusion and according to Eyink et al. (2011) the reconnection follows the laws established in LV99. In other words, on scales significantly larger than the viscous damping scale LV99 reconnection is applicable. At the same time on scales less than L_{RR} magnetic reconnection may be slow³. Somewhat more complex arguments were employed in Lazarian et al. (2004) to prove that the reconnection is fast in the partially ionized gas. For our further discussion it is important that LV99 model is applicable both to fully ionized and partially ionized plasmas.

5. Testing of LV99 predictions and Richardson diffusion

Simulations in Kowal et al. (2009, 2012) confirmed no dependence of turbulent reconnection on resistivity and provided good correspondence to the LV99 analytical predictions the injection power, i.e. $V_{rec} \sim P_{inj}^{1/2}$. The corresponding dependence is shown in Figure 2.

As we discussed, the LV99 model is intrinsically related to the concept of Richardson diffusion in magnetized fluids. Thus by testing the Richardson diffusion of magnetic field, one also provides tests for the theory of turbulent reconnection.

The first numerical tests of Richardson diffusion were related to magnetic field wandering predicted in LV99 Maron et al. (2004); Lazarian et al. (2004). In Figure 3 we show the results obtained in Lazarian et al. (2004). There we clearly see different regimes of magnetic field diffusion, including the $y \sim x^{3/2}$ regime. This is a manifestation of the spatial Richardson diffusion.

³Incidentally, this can explain the formation of density fluctuations on scales of thousands of Astronomical Units, that are observed in the ISM.

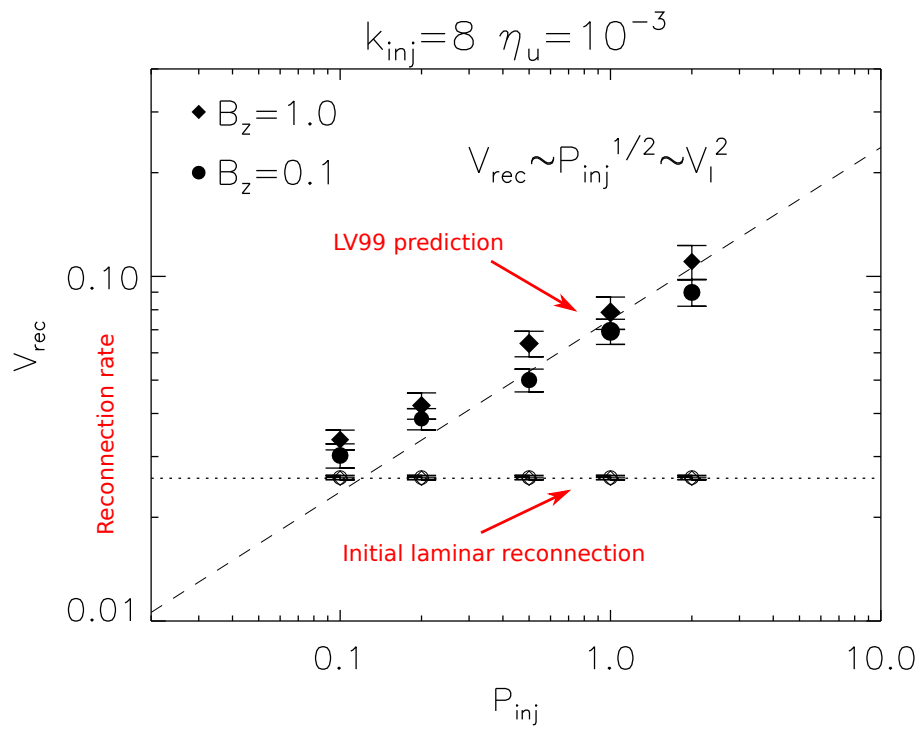


Figure 2. The dependence of the reconnection velocity on the injection power for different simulations with different drivings. The predicted LV99 dependence is also shown. P_{inj} and k_{inj} are the injection power and scale, respectively, B_z is the guide field strength, and η_u the value of uniform resistivity coefficient. From Kowal et al. (2012).

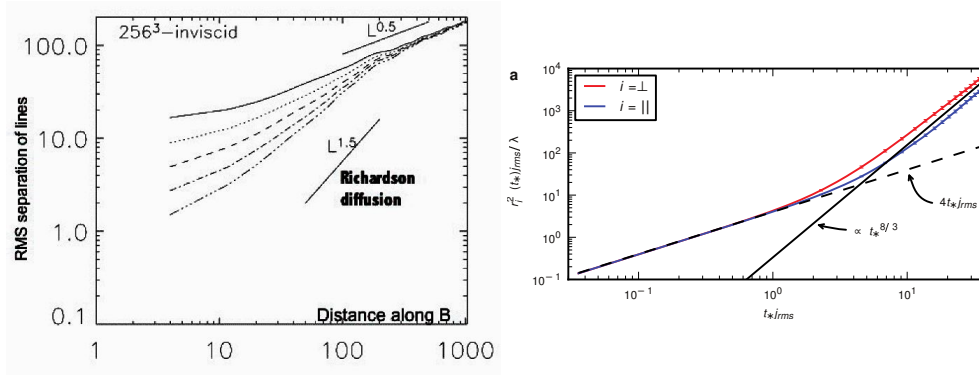


Figure 3. *Left panel.* Richardson diffusion of magnetic field lines in space. From Lazarian et al. (2004) *Right panel.* Stochastic trajectories that arrive at a fixed point in the archived MHD flow, color-coded red, green, and blue from earlier to later times. From Eyink et al. (2013).

A numerical study of the temporal Richardson diffusion of magnetic field-lines was performed in Eyink et al. (2013). For this experiment, stochastic fluid trajectories had to be tracked backward in time from a fixed point in order to determine which field lines at earlier times would arrive to that point and be resistively “glued together”. Hence, many time frames of an MHD simulation were stored so that equations for the trajectories could be integrated backward. The results of this study are illustrated in Figure 3. It shows the trajectories of the arriving magnetic field-lines, which are clearly widely dispersed backward in time, more resembling a spreading plume of smoke than a single “frozen-in” line.

The implication of these results is that standard diffusive motion of field-lines holds for only a very short time, of order of the resistive time, and is then replaced by super-diffusive, explosive separation by turbulent relative advection. This same effect should occur not only in resistive MHD but whenever there is a long power-law turbulent inertial range. Whatever plasma mechanism of line-slippage holds at scales below the ion gyroradius—electron inertia, pressure anisotropy, etc.—will be accelerated and effectively replaced by the ideal MHD effect of Richardson dispersion.

6. Observational testing of LV99

Qualitatively, one can argue that there is observational evidence in favor of the LV99 model. For instance, observations of the thick reconnection current outflow regions observed in the Solar flares (Ciaravella & Raymond 2008) were predicted within LV99 model at the time when the competing plasma Hall term models were predicting X-point localized reconnection. However, as plasma models have evolved since 1999 to include tearing and formation of magnetic islands (see Drake et al. 2010) it is necessary to get to a quantitative level to compare the predictions from the competing theories and observations.

To be quantitative one should relate the idealized model LV99 turbulence driving to the turbulence driving within solar flares. In LV99 the turbulence driving was assumed isotropic and homogeneous at a distinct length scale L_{inj} . A general difficulty

with observational studies of turbulent reconnection is the determination of L_{inj} . One possible approach is based on the relation $\varepsilon \approx u_L^4/V_A L_{inj}$ for the weak turbulence energy cascade rate. The mean energy dissipation rate ε is a source of plasma heating, which can be estimated from observations of electromagnetic radiation (see more in Eyink et al. 2011). However, when the energy is injected from reconnection itself, the cascade is strong and anisotropic from the very beginning. If the driving velocities are sub-Alfvénic, turbulence in such a driving is undergoing a transition from weak to strong at the scale LM_A^2 (see §4). The scale of the transition corresponds to the velocity $M_A^2 V_A$. If turbulence is driven by magnetic reconnection, one can expect substantial changes of the magnetic field direction corresponding to strong turbulence. Thus it is natural to identify the velocities measured during the reconnection events with the strong MHD turbulence regime. In other words, one can use:

$$V_{rec} \approx U_{obs,turb}(L_{inj}/L_x)^{1/2}, \quad (8)$$

where $U_{obs,turb}$ is the spectroscopically measured turbulent velocity dispersion. Similarly, the thickness of the reconnection layer should be defined as

$$\Delta \approx L_x(U_{obs,turb}/V_A)(L_{inj}/L_x)^{1/2}. \quad (9)$$

Naturally, this is just a different way of presenting LV99 expressions, but taking into account that the driving arises from reconnection and therefore turbulence is strong from the very beginning (see more in Eyink et al. (2013)). The expressions given by Eqs. (8) and (9) can be compared with observations in Ciaravella & Raymond (2008). There, the widths of the reconnection regions were reported in the range from $0.08L_x$ up to $0.16L_x$ while the the observed Doppler velocities in the units of V_A were of the order of 0.1. It is easy to see that these values are in a good agreement with the predictions given by Eq. (9).

In addition, in Sych et al. (2009), the authors explaining quasi-periodic pulsations in observed flaring energy releases at an active region above the sunspot, proposed that the wave packets arising from the sunspots can trigger such pulsations. This is exactly what is expected within the LV99 model. We are not aware of any other model of reconnection that would predict such a triggering.

The criterion for the application of LV99 theory is that the outflow region is much larger than the ion Larmor radius $\Delta \gg \rho_i$. This is definitely satisfied for the solar atmosphere where the ratio of Δ to ρ_i can be larger than 10^6 . Plasma effects can play a role for small scale reconnection events within the layer, since the dissipation length based on Spitzer resistivity is ~ 1 cm, whereas $\rho_i \sim 10^3$ cm. However, as we discussed earlier, this does not change the overall dynamics of turbulent reconnection.

Reconnection throughout most of the heliosphere appears similar to that in the Sun. For example, there are now extensive observations of reconnection jets (outflows, exhausts) and strong current sheets in the solar wind (Gosling 2012). The most intense current sheets observed in the solar wind are very often not observed to be associated with strong (Alfvénic) outflows and have widths at most a few tens of the proton inertial length δ_i or proton gyroradius ρ_i (whichever is larger). Small-scale current sheets of this sort that do exhibit observable reconnection have exhausts with widths at most a few hundreds of ion inertial lengths and frequently have small shear angles (strong guide fields) (Gosling et al. 2007; Gosling & Szabo 2008). Such small-scale reconnection in the solar wind requires collisionless physics for its description, but the observations are

exactly what would be expected of small-scale reconnection in MHD turbulence of a collisionless plasma (Vasquez et al. 2007). Indeed, LV99 predicted that the small-scale reconnection in MHD turbulence should be similar to large-scale reconnection, but with nearly parallel magnetic field lines and with “outflows” of the same order as the local, shear-Alfvénic turbulent eddy motions.

However, there is also a prevalence of very large-scale reconnection events in the solar wind, quite often associated with interplanetary coronal mass ejections and magnetic clouds or occasionally magnetic disconnection events at the heliospheric current sheet (Phan et al. 2009; Gosling 2012). These events have reconnection outflows with widths up to nearly 10^5 of the ion inertial length and appear to be in a prolonged, quasi-stationary regime with reconnection lasting for several hours. Such large-scale reconnection is as predicted by the LV99 theory when very large flux-structures with oppositely-directed components of magnetic field impinge upon each other in the turbulent environment of the solar wind. The “current sheet” producing such large-scale reconnection in the LV99 theory contains itself many ion-scale, intense current sheets embedded in a diffuse turbulent background of weaker (but still substantial) current. Observational efforts addressed to proving/disproving the LV99 theory should note that it is this broad zone of more diffuse current, not the sporadic strong sheets, which is responsible for large-scale turbulent reconnection. Note that the study (Eyink et al. 2013) showed that standard magnetic flux-freezing is violated at general points in turbulent MHD, not just at the most intense, sparsely distributed sheets. Thus, large-scale reconnection in the solar wind is a very promising area for LV99. The situation for LV99 generally gets better with increasing distance from the sun, because of the great increase in scales. For example, reconnecting flux structures in the inner heliosheath could have sizes up to ~ 100 AU, much larger than the ion cyclotron radius $\sim 10^3$ km (Lazarian & Opher 2009).

The magnetosphere is another example that is under active investigation by the reconnection community. The situation there is different, as $\Delta \sim \rho_i$ is the general rule and we expect plasma effects to be dominant.

6.1. Self-sustained turbulent reconnection

If the initial magnetic field configuration is laminar, magnetic reconnection ought to induce turbulence due to the outflow (LV99). This effect was confirmed by observing the development of turbulence both in recent 3D Particle in Cell (PIC) simulations (Karimabadi et al. 2013) and 3D MHD simulations (Beresnyak 2013; Kowal et al. 2014).

Recent simulations from Kowal et al. (2014) are presented in Figure 4. The figure shows a few slices of the magnetic field strength $|\vec{B}|$ through the three-dimensional computational domain with dimensions $L_x = 1.0$ and $L_y = L_z = 0.25$. The simulation was done with the resolution $2048 \times 512 \times 512$. Open boundary conditions along the X and Y directions allowed studies of steady state turbulence. At the presented time $t = 1.0$ the turbulence strength increased by two orders of magnitude from its initial value of $E_{kin} \approx 10^{-4} E_{mag}$. Initially, only the seed velocity field at the smallest scales was imposed (a random velocity vector was set for each cell). We expect that most of the injected energy comes from the Kelvin-Helmholtz instability induced by the local interactions between the reconnection events, which dominates in the Z-direction, along which a weak guide field is imposed ($B_z = 0.1 B_x$). As seen in the planes perpendicular to B_x in Figure 4, Kelvin-Helmholtz-like structures are already well developed at time

$t = 1.0$. Turbulent structures are also observed within the XY-plane, which probably are generated by the strong interactions of the ejected plasma from the neighboring reconnection events.

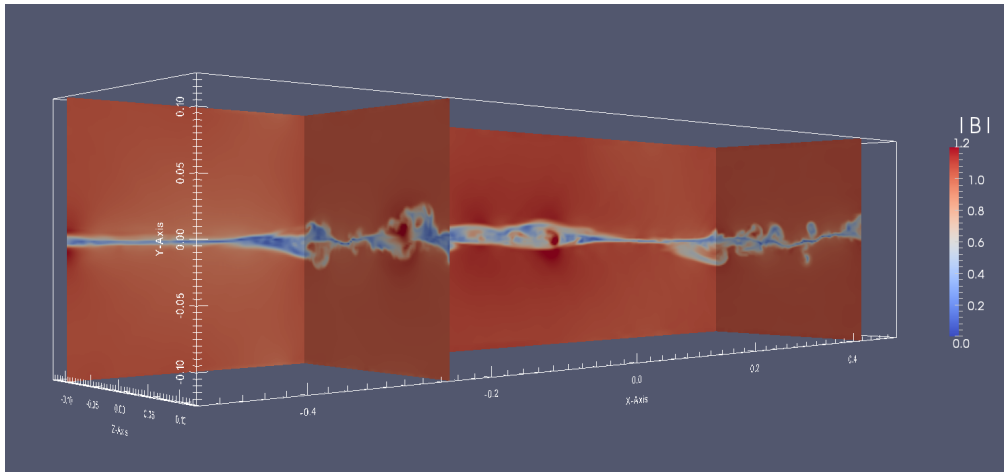


Figure 4. Visualization of the model of turbulence generated by the seed reconnection from Kowal et al. (2014). Three different cuts (one XY plane at $Z=-0.1$ and two YZ-planes at $X=-0.25$ and $X=0.42$) through the computational domain show the strength of magnetic field $|\vec{B}|$ at the evolution time $t = 1.0$. Kelvin-Helmholtz-type structures are well seen in the planes perpendicular to the reconnecting magnetic component B_x . In the Z direction, the Kelvin-Helmholtz instability is slightly suppressed by the guide field of the strength $B_z = 0.1B_x$ (with $B_x = 1.0$ initially). The initial current sheet is located along the XZ plane at $Y=0.0$. A weak ($E_{kin} \approx 10^{-4}E_{mag}$) random velocity field was imposed initially in order to seed the reconnection.

7. Mean field approach and turbulent reconnection

The relation of turbulence and reconnection has attracted more attention recently. For instance, Guo et al. (2012) proposed a model based on the earlier idea of mean field approach suggested initially in Kim & Diamond (2001). In the latter paper the author concluded that the reconnection rate should be always slow in the presence of turbulence. On the contrary, models in Guo et al. (2012) invoke hyperresistivity and get fast reconnection rates. Similarly, invoking the mean field approach Higashimori & Hoshino (2012) presented their model of turbulent reconnection.

The mean field approach invoked in the aforementioned studies was critically analyzed by Eyink et al. (2011), and below we briefly present some arguments from that study. The principal difficulty is with the justification of using the mean field approaches to explain fast magnetic reconnection. In such an approach effects of turbulence are described using parameters such as anisotropic turbulent magnetic diffusivity and hyper-resistivity experienced by the fields once averaged over ensembles. The problem is that it is the lines of the full magnetic field that must be rapidly reconnected, not just the lines of the mean field. Eyink et al. (2011) stress that the former implies the latter, but not conversely. No mean-field approach can claim to have explained the

observed rapid pace of magnetic reconnection unless it is shown that the reconnection rates obtained in the theory are strictly independent of the length and timescales of the averaging. More detailed discussion of the conceptual problems of the hyper-resistivity concept and mean field approach to magnetic reconnection is presented in Lazarian et al. (2004) and Eyink et al. (2011).

8. Summary

The studies on turbulent magnetic reconnection has shown

- Turbulence makes reconnection fast, i.e. independent of resistivity.
- Turbulence ubiquitous in astrophysics, but reconnection itself induces turbulence.
- Numerical simulations and observational data are consistent with the turbulent reconnection being the dominant mechanism of astrophysical reconnection.

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